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Zbigniew Jan SROKA
Rafał HEDA

Combustion Engines
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Experimental verification of changes in the control map of a diesel engine operation due to fuel consumption

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The paper describes an experiment related to the introduction of changes in the control software of a supercharged diesel engine in order to reduce fuel consumption, as a measure of useful efficiency. The map shaping the torque in the range of low and medium engine speeds was modified. The fuel dose for a specific engine speed at maximum engine load was changed, and the boost pressure was increased without exceeding the permissible values. A vehicle from the age group of 16 years – typical for the automotive market in Poland, was selected for the tests. It meets the Euro 5 standard. The experiment was carried out on a chassis dynamometer and in road traffic conditions. The average fuel consumption was obtained lower by 0.4 dm^3 per 100 km than the factory assumed.

Key words: *engine control map, fuel consumption, tests*

1. Introduction

Improving the combustion engine in order to increase its useful efficiency is a reflection of energy limitations, which are, among other things, the basis for modifying means of transport towards the development of hybrid drives. For many years, the dominant factor in the development of combustion engines has been broadly defined ecology, which results from the combustion process, and its main determinant is fuel consumption. The research problem discussed in this manuscript is precisely fuel consumption, which is, among other things, a derivative of the engine control process. In the past, this aspect was called "engine liquid fuel economy". Today, it has a broader meaning, hence the initial review of emission standards, but it is only related to diesel drives for passenger cars. Fuel consumption has a direct impact on carbon dioxide emissions, but in terms of standards, appropriate provisions have only recently appeared.

For diesel engines of passenger cars manufactured and circulating in the European Union, the Euro 1 standard was introduced in 1993. At that time, permissible emission values of carbon monoxide (3.16 g/km), hydrocarbons including nitrogen oxides (1.13 g/km) and the mass of particulate matter (0.18 g/km) were specified. Just a few years later, through the Euro 3 standard, these values were significantly reduced [16, 27] while at the same time, categorizing nitrogen oxides as highly harmful to the environment (0.50 g/km) were separated. In subsequent editions, the emission levels of these substances were reduced. In the Euro 5b standard, in 2011, a new parameter was introduced – the number of particulate matter, setting their emission at the level of 6.0×10^{11} 1/km. In the Euro 6d standard, in force since September 2014, together with numerous modifications in the following years, the permissible value of NO_x emissions was significantly reduced to 0.08 g/km. The emission of the combined component HC + NO_x was also reduced from 0.23 (Euro 5b) to 0.17 g/km. Emissions of other exhaust gas components were maintained at previous levels, i.e., for CO 0.50 g/km and PM 0.0045 g/km. The Euro 7 standard, scheduled for November 2026, is primarily intended to enforce testing methods according to WLTP and RDE procedures [4, 10, 13].

The implementation of engine emission standards has led to the development of many exhaust gas cleaning systems that have been fitted to engines to meet the standard. The first step was the introduction of catalytic converters to exhaust systems [9, 25], then exhaust gas recirculation systems [21] and particulate filters [14].

In the following years, additional exhaust gas purification systems were designed mainly for diesel engines, such as particulate filters [14], selective catalytic reduction systems [12], or catalysts inside the combustion chamber [3, 22].

An important element of progress in reducing exhaust gas pollution is electronic support in the management of engine operation, especially in terms of air supply and exhaust gas control. The internal combustion engine power management system controls the correct operation of the unit and controls the selection of the fuel mixture, which translates into fuel consumption and the quality of exhaust gases. The computer collects signals from individual sensors, processes them, and regulates the amount of fuel used in relation to the environmental operating conditions and the unit load. An example is the expansion of the direct injection system with an air mass meter, which allows determining the share of exhaust gas recirculation in the intake manifold along with limiting the degree of smoke in all unit operating conditions [24, 29]. In turn, turbocharged diesel engines, in which the controllers control the operations of the turbochargers, are additionally equipped with a boost pressure sensors [1, 30].

In the care for the environment, it is impossible to ignore the considerations on the complete change of the fuel supply method that occurred with the application of the common rail system. Obtaining subsequent levels of exhaust emission standards results from the possibility of organizing a very high fuel pressure and precise control of the injectors, with the possibility of injecting several doses during one work cycle [23, 26].

The fuel pressure value affects the atomization of diesel oil droplets in the combustion chamber, which results in better mixing of fuel with air [20]. By obtaining a higher maximum pressure, the fuel dose can be increased, and the engine characteristics can be improved throughout the entire operating range without impairing the combustion process.

Verification tests have a major impact on the performance characteristics of engines meeting a given Euro standard. The standardized NEDC driving cycle introduced in 1992, applicable to all passenger cars and light commercial vehicles, assumed the measurement of fuel consumption and exhaust emissions in such a way that the obtained results were comparable between the tested vehicles. Unfortunately, it did not meet environmental expectations due to data falsification using software that was deliberately designed so that emission limits were activated only during laboratory control tests. The installed software caused nitrogen oxides emissions in the German manufacturer's vehicles to meet American standards during the required tests, but when driving in road conditions they were many times higher [7]. Among other reasons, it was recognized that it was necessary to modify the testing method in terms of dynamic driving style and to standardize the measurement procedure at the global level by combining the WLTP procedure with RDE [6].

The test parameters are designed to ensure that values are representative of the real driving cycle. Currently, the test results obtained in the WLTP laboratory test must be correlated with the RDE road test, which checks, using portable PEMS measuring devices, whether cars maintain the target emission levels in real driving conditions [2, 8].

Both in theory and in practice, development work on the use of electronic engine control systems plays a significant role in increasing the efficiency of the combustion process [5, 15, 19]. These works are carried out in various aspects, such as [18], in which the Tuning Box was examined in relation to a diesel engine with a Common Rail fuel supply system, determining the effect on the power and torque performances. In another work [17], the authors assessed the effect of modification of control maps on CO, CO_2, PM and NO_x exhaust emissions in real operating conditions using PEMS measuring devices. The research concerned a vehicle from the Euro 3 emission group.

Following this trend and considering the engine operation area at low and medium engine speeds as dominant in operation, the authors modified the engine control map shaping the torque field. The fuel dose was changed, which was reflected in the change of the injection pressure executive map. The boost pressure was also increased. The main goal of these studies was to demonstrate the possibility of personalizing the engine control to achieve an ecological effect understood jointly as a reduction in fuel consumption and the effects in the form of reduced carbon dioxide emissions without interfering with the engine design structure. The described research results are part of a broader project, the aim of which is to demonstrate the degree of differentiation in the possibilities of electronic impact on vehicles of different age groups. These studies do not constitute an absolute novelty but are a voice in the discussion on that subject.

2. Research methodology and measurement results

2.1. Object of research

A vehicle with a 2.0 dm^3 diesel engine, equipped with a common rail fuel system and a turbocharger with variable geometry of the compressor blades, was selected for the tests. The vehicle met the Euro 5 emission standard. The vehicle was manufactured in 2007, which is consistent with the considerations on the assessment of passenger cars in the average age group estimated at over 16 years in Poland (after taking into account the so-called "dead souls", i.e. unused and unregistered vehicles) [28]. Research on such cars can be considered up-to-date and accurate, as they constitute 35–40% of all vehicles in Poland.

The vehicle manufacturer declared a maximum engine (with code CBAB) power of 103 kW at 4000 rpm and a maximum torque of 320 Nm at 1800 rpm. The engine control unit was the EDC17CP14 module.

The vehicle on which the tests were carried out was equipped with a six-speed hydrokinetic automatic transmission, which helped reduce steering errors with a manual gearbox, but above all, there was no need to shift the load point of the TCU.

The experiment was carried out in three stages. The first stage consisted of a multi-variant modification of the engine control map. The second stage involved testing in laboratory conditions on a chassis dynamometer and finally, during the third stage, tests were carried out in road conditions.

2.2. Modification of the engine control map

The engine control map modification resulted in a change in the torque characteristics so that the vehicle would reach the desired speed faster while automatically reaching the highest possible gear. The torque distribution in the low and medium engine speed range was improved. It was assumed that the increase in torque while reducing the engine speed would result in a reduction in fuel consumption, according to the performance map. The direct effect of this action will be a reduction in the time of "shifting" to a higher gear, which at the same driving speed will reduce the overload of the drive unit, and this will additionally improve the level of unit reliability [11]. The modified map shaping the engine torque is presented in Fig. 1.

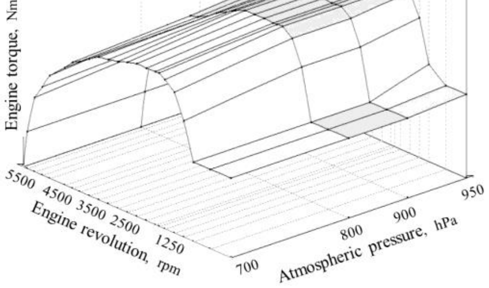

Fig. 1. The main map shaping the engine torque after modification

The engine control map (Fig. 1 and Table 1) shapes the torque curve with the increase in engine speed relative to atmospheric pressure.

Table 1. Part of the map converting the desired torque into fuel dose [mg/stroke]

		Engine torque [Nm]								
		0	25	70	120	180	240	300	360	390
Engine revolution [rpm]	800	0.00	5.59	12.13	21.50	32.00	48.21	63.42	76.25	81.88
	1000	0.00	5.25	11.50	20.64	30.89	44.72	59.00	71.92	77.67
	1250	0.00	4.90	11.12	19.98	30.01	41.50	53.89	66.70	72.69
	1500	0.00	4.50	10.84	19.67	29.03	39.89	50.80	63.07	69.20
	1750	0.00	3.91	10.40	19.30	28.26	38.75	48.37	60.54	66.96
	2000	0.00	3.66	10.21	18.85	27.68	38.04	47.18	58.70	65.02
	2250	0.00	3.34	9.86	18.46	27.23	38.03	47.35	58.49	64.66
	2500	0.00	3.02	9.50	18.07	26.78	38.03	47.51	58.27	64.30
	2750	0.00	2.82	9.19	17.61	26.34	37.96	48.14	59.10	65.09
	3000	0.00	2.54	8.65	17.10	25.89	37.40	48.05	59.59	65.59
	3250	0.00	2.48	8.27	16.20	25.44	36.83	47.93	59.59	65.38
	3500	0.00	2.25	7.95	15.41	24.99	36.16	47.75	59.75	65.38
	3750	0.00	2.50	7.71	14.87	24.64	35.98	48.26	60.42	65.88
	4000	0.00	2.70	7.63	14.29	25.14	36.56	49.19	61.20	66.60
	4250	0.00	2.84	7.98	14.62	25.51	37.45	50.53	62.40	67.70
	4500	0.00	3.10	8.47	14.87	25.89	38.07	51.57	63.42	68.58

This map also limits the engine's operation according to full-load characteristics. To obtain an increase in torque, the limit values had to be increased relative to the standard settings. During the experiment, the torque values were increased by 50 Nm in the engine speed range from 1500 to 3500 rpm. In this way, for example, at an engine speed of 2000 rpm and for maximum engine load, the fuel dose increased by 10 mg per single stroke. The fuel dose increase values can be read from the map, which converts the desired engine torque calculated by the controller into a specific value required at a given engine operating point. When the desired value exceeds the map range, it is possible to use the extrapolation function and determine values for interesting operating points.

When modifying the control map, attention was also paid to the quality of fuel atomization. The fragmentation of fuel droplets, improving the efficiency of fuel contact with the oxidizer, was achieved by increasing the injection pressure by 5% starting from a dose of 35 mg/stroke, i.e., the value defining the beginning of the maximum torque area. The control program also contains maps specifying the permissible air-fuel ratio in relation to the engine load and revolution, as well as maps specifying the maximum fuel dose for a given air mass flow and boost pressure. None of these maps have been modified because the engine is equipped with a diesel particle filter. Lowering the lambda coefficient could cause faster contamination of the filter and more frequent automatic regeneration, which may result in premature wear. The concept of automatic regeneration should be understood as the combustion of particulate matter in order to unblock the correct flow of gases in the exhaust system. Such regenerations are a normal process that the control program takes into account. Each filter regeneration process increases fuel consumption, which is why this system was left to operate as intended and assumed, and the combustion process occurred as rarely as possible. The modification of the engine control map also concerned increasing the boost pressure in the range in which the changes were made in order to obtain a greater airflow and a complete filling of the combustion chamber. In this way, the lambda coefficient value was maintained at the level of 1.15 for low engine speeds and 1.30 for medium and high engine speeds. The previously mentioned maps limiting the fuel dose in relation to the flow and boost pressure and the lambda coefficient were left unchanged – Fig. 2.

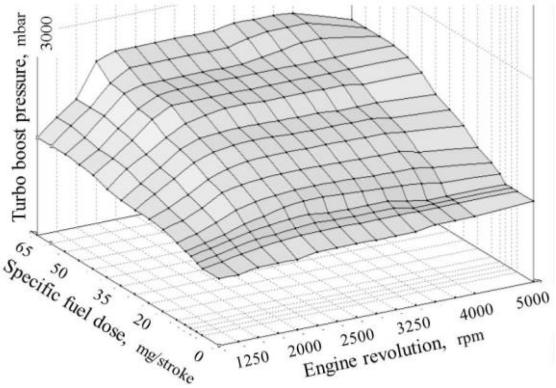

Fig. 2. Turbocharger boost pressure regulating map

Taking into account the ambient pressure of 1010 mbar, the boost pressure for the maximum fuel dose was approximately 2550 mbar. The boost pressure values for partial load at the lowest possible engine speeds were also modified.

2.3. Laboratory test on a chassis dynamometer

The laboratory tests were carried out on the MAHA LPS3000 chassis dynamometer, which is part of the measuring equipment of the Department of Automotive Engineering at the Wrocław University of Science and Technology (WUST). The technical parameters of the test stand ensured free measurements of the power of the drive unit, the power at the vehicle wheels and the torque as a function of the engine speed – Fig. 3.

Fig. 3. Tested vehicle on the chassis dynamometer at the Department of Automotive Engineering, WUST

The modification of the control map resulted in a change in the full-load characteristics, with a maximum increase in torque by 62 Nm to 382 Nm at 2040 rpm and a power increase by 30 kW to 133 kW at 4120 rpm – Fig. 4.

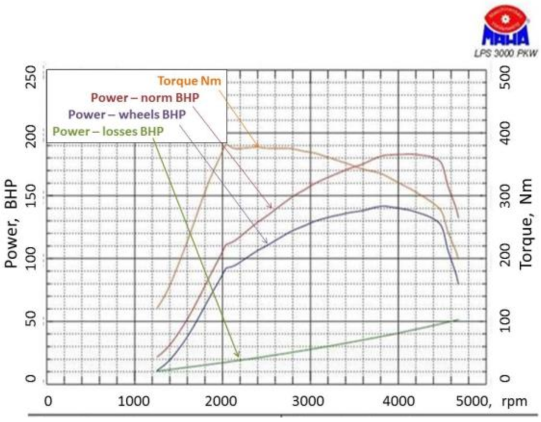

Fig. 4. Full-load characteristics after changes to the engine control settings

The study identified two cycles. One was urban driving, and the other was rural operating conditions. The majority of the cycle was urban, with momentary stops. In such a situation, the start-stop system plays a major role, as it affects the concentration of harmful substances in exhaust gases. By focusing on the modification results, it was possible to verify them using an OBD device. In this way, the following were assessed: air mass flow, boost pressure and fuel-air ratio. The obtained data fully confirmed the values assumed during map modification, e.g., air flow provided a lambda coefficient above 1.15 for engine speeds between 1000–2500 rpm. This results from the engine characteristics that are obtained, which cause the engine to have higher engine torque in the lower engine rotation range, which also translates into reduced fuel consumption.

2.4. Road test

The road test of fuel consumption was connected with driving a specific distance. During the tests, the vehicle "drove" a total of 976 km, of which 496 km was on the serial control program and 480 km was on the modified one. During the experiment, the car was used by one driver. A vehicle with an automatic transmission was deliberately selected for the test to reduce the user's influence on the selection of the gear ratio. The vehicle was driven from point A (Dębowiec) to point B (Prudnik, Jesionkowa Str.) – Fig. 5.

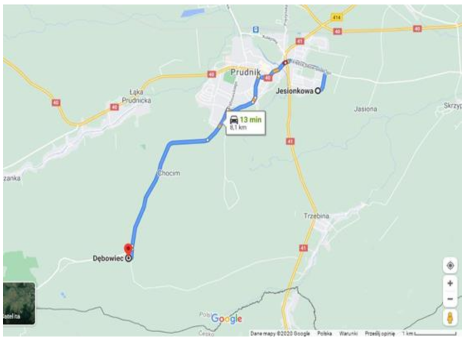

Fig. 5. Road test – driving route (source: Google Maps)

The 8 km route was covered daily for 61 days in both directions, thus eliminating the influence of terrain, weather conditions and driving diversification resulting from traffic density. The vehicle was driven on paved roads in the urban cycle (a small town with a population of approx. 20 thousand) and rural cycle. In the urban cycle, the car covered 45% of the route, of which 4% was an unpaved road. During the urban journey, the vehicle most often stopped for short periods (a few seconds). The speed of the urban journey did not exceed 50 km/h, while the rural speed was up to 90 km/h.

Due to the preliminary tests and the multiple runs, it was decided that at this stage of the research, the fuel consumption would be measured using the full tank method when verifying the OBD system. The carbon dioxide emission assessment is a theoretical result. In this way, it was possible to initially identify the real problem. In the next stage of the project, PEMS will be used. Then, the concentration values will also be measured and the emissions of other harmful substances will be determined to obtain a full view of the impact of the modifications applied.

By modifying the control program as described in Chapter 2.2, the engine torque curve distribution was improved. The characteristics of the automatic transmission operation were changed and the average fuel consumption was achieved at the level of 7.8 dm^3/100 km, which compared to the value of 8.2 dm^3/100 km for the standard control map means a reduction in fuel consumption by almost 5%. Given the generally accepted relationship that 2.7 kg of carbon dioxide is generated from the burnt 1 dm^3 of diesel fuel, the reduction in fuel consumption means a smaller mass of CO_2 emitted into the atmosphere by 1.8 kg, which translates into carbon dioxide emissions over the distance covered of 221 g/km for the standard map and 211 g/km after modification, respectively – Table 2.

Table 2. Selected road test indicators

	Standard map	Map after modification
Distance, km	480	496
Average measured fuel consumption, dm^3/100 km	8.20	7.80
Cumulative measured fuel consumption, dm^3	39.36	38.69
Theoretical mass of emitted CO_2, kg	106.27	104.46
Theoretical CO_2 emissions, g/km	221	211

Reducing fuel consumption, of course, also has a positive financial aspect, but its absolute value is derived from fuel prices.

3. Conclusion

The article presents the results of development work on the modification of the engine control map shaping the torque field in terms of fuel consumption. In this way, the trend of personalizing the engine operation to achieve an ecological effect without interfering with the engine design was included.

The research concerned the turbo diesel engine operation area at low and medium engine speeds, considering this range as dominant in operation. The fuel dose was changed, which was reflected in the change of the injection pressure executive map. The boost pressure was also increased. The obtained results in the form of a reduction in measured fuel consumption and a theoretical reduction in carbon dioxide emissions confirmed the validity of the adopted assumptions.

This has demonstrated the possibility of reducing carbon dioxide emissions, thereby creating the potential to reduce global warming.

For example, in vehicle meeting the EURO 5 standard, changes were made to the control software, which affected the change of the engine torque curve in the entire operating range. This translated into engine efficiency, automatic transmission operation and driver's driving style. The average fuel consumption was lower by 0.4 dm^3 for every 100 km of driving, positively affecting the environment by reducing CO_2 emissions by almost 5% during a 496 km route with a modified engine control map.

The results achieved are the basis for further tests with vehicles from different emission groups. However, these tests should be carried out according to the currently applicable RDE and WLTP procedures using PEMS measuring equipment. The Department of Automotive Engineering has such devices. A route has also been developed that meets the standards requirements.

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Nomenclature

NEDC	New European Driving Cycle
OBD	on board diagnostics
PEMS	portable emission measurement system
RDE	real driving emissions
TCU	transmission control unit
WLTP	Worldwide Harmonized Light Vehicle Test Procedure

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Zbigniew J. Sroka, DSc., DEng. – Faculty of Mechanical Engineering, Wrocław University of Science and Technology, Poland.
e-mail: *zbigniew.sroka@pwr.edu.pl*

Rafał Heda, MSc. – RSH Auto-Centrum, Poland.
e-mail: *rafalheda09@gmail.com*